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January 28, 1966

SA-9991-4

Re: 22-009-002

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SUBJECT: Progress Report for the Period 1 April 1965 through 30 September 1965 - NsG 107-61.

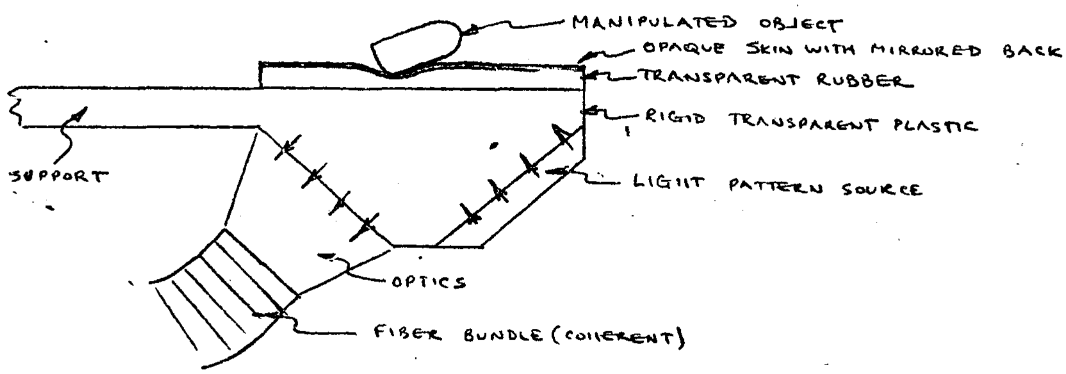
Progress for this period is reported in the following categories:

1. Development of a spatially continuous remote touch sensor - T. G. Strickler.
2. Force feedback with delay - W. R. Ferrell.
3. Simulation study of supervisory control of a manipulator using entirely computer simulated task for the human operator - S. G. McCandlish.
4. Simulation study of supervisory control of a manipulator using an actual manipulator and mechanical environment - T. D. Rarich and J. D. Barber.
5. Dynamic programming model of preview control - P. A. Hardin.

1. Development of a spatially continuous remote touch sensor - T. G. Strickler

Since the last progress report the Moire principle which at that time looked the most promising has been abandoned due to difficulties in getting sharp focus simultaneously on the rigid (reference) grid and on the flexible (skin surface) grid.

A new and simpler approach is being taken, which involves a direct reflection of a geometric light pattern off a mirror which constitutes the back side of the skin surface itself. This produces distortions in the regular (polka dot or rectangular grid) pattern of magnitude and spatial extent which correspond roughly (but not exactly) to the normal strain pattern of the skin surface.



This principle has been emobdied in a prototype as diagrammed above, which has been demonstrated successfully using closed circuit television.

Currently a touch sensor instrument is being fabricated specifically to attach to the AMF Model 8 manipulator for further experiments in the context of remote handling of actual objects.

2. Force feedback with delay - W. R. Ferrell

The operator of a remote manipulator normally needs information concerning the forces exerted on the remote hand both to assess the dynamic characteristics of objects in the remote environment and to enable him to make movements which conform to kinematic constraints without over-stressing the manipulator or objects in the environment - as when a door is opened. When there are long transmission delays the force feedback is out of date, and experiments have been undertaken to determine the effects of delays on the use of force information. The apparatus used has been a one-dimensional remote positioning device with forces measured by strain gauges and fed back to the operator by means of a motor connected to his control. The experimental results have indicated:

1. A remote hand can be positioned in response to force information alone in spite of delay of from 0.3 to 30 seconds.
2. When objects are being searched for and the only feedback is from contact forces performance is slightly faster if an operator uses continuous searching motion rather than a series of moves and waits as was found best with visual feedback.[1]
3. If the feedback gain is sufficiently great or if the forces encountered are sufficiently large, serious instabilities can occur with delay. Unstable situations can be of two kinds:
    a. If the remote hand is in a force field an oscillatory instability can result.
    b. If contact with a fixed or massive object is attempted the remote hand will bounce off the object and it will be difficult or impossible to maintain contact.
4. Instabilities can be avoided and positioning still accomplished by applying the feedback forces to other parts of the body - specifically the hand not moving the control.

It is anticipated that, in view of the above conclusions, force feedback should be a capability of remote manipulators used when very long transmission distances cause delays. However, the forces feedback should be displayed to the operator in such a way that they do not affect the movements of the master control. Lights or vibratory inputs to the skin are possible methods.

3. <u>Simulation study of supervisory control of a manipulator using entirely computer simulated task for the human operator</u> - S. G. McCandlish. (This phase of the project is being jointly supported by the U. S. Air Force)

A digital computer program called JAWS has been written for use on the PDP-1 computer which belongs to the Research Laboratory of Electronics at M.I.T. This program is a manipulative task simulator which may be had to measure a human operator's performance as various parameters of the man-machine interface and of the simulated task are varied.

The manipulative task is two-dimensional. An object has to be moved from its initial position and placed in a hole. The object may be grasped by a pair of "jaws" which may be moved in the horizontal and vertical directions, and opened or closed by the operator. The latter has direct control of the jaws through two kinds controlled potentiometer which provide velocity control of the motions, and he controls the open-close movement through a set of 18 switches. Three preprogrammed combinations of these motions are available (through the switches) to perform those operations where accurate performance is demanded of the operator by the physical constraints of the environment, and where a mistake rewritten is an error signal from the computer. The operator views a representation of the task on a 10 inch display tube.

The parameters of the task itself that may be varied are: (1) the tolerance permitted the operator in each phase of his task, and (2) the mass of the object. The parameters of the man-machine interface include (1) the transmission delay between operator and system, (2) the proportion of time that the display is visible to the operator, (3) the nature of the display (static or continuous), and (4) the resolution of the display (maximum 50 points per inch). To improve the reality of the simulation the following features were built into the program. The object, an unstable rectangle, will fall over if excessive force is applied from only one side. The object will fall as in a gravity field if it is released, and on reaching the ground will either rebound or cause an error return depending on the effective velocity of impact.

A "run" is concluded either when the operator presses the "completed" button or when the program generates an error return. The following information is typed out after each "run": the time taken, number of instructions generated by the operator, the distance travelled, and the integrated sum of the absolute acceleration.

At this time approximately 55 hours of experimental time have been run, using 3 subjects each of whom had previously had approximately 6 hours practice. In these tasks three parameters were varied; the mass of the object (dynamic time constant at 1/4 second, 1 second, 8 seconds); the transmission delay (0 second, 1/4 second, 3 seconds) and display rate (continuous, and 1/2 second vision every 4 seconds). The operator had only direct control over the "jaws", without the option of using the pre-programmed routines.

4. Simulation study of supervisory control of a manipulator using an actual manipulator and mechanical environment - T. D. Rarich and J. D. Barber.

A standard American Machine and Foundry Model8 master-slave manipulator has been modified to include, among other things, elementary touch sensors on its manipulating surfaces. (This is basically the same manipulator used by H. Ernst in a 1961 ScD. Thesis). It is now being interfaced with a Digital Equipment Corp., PDP-8 computer to provide a simulator by which a variety of remote manipulation studies may be performed with an actual human operator in a real time supervisory control loop.

In this situation the man controls the mechanical arm and hand through an intermediate computer. In a space application both computer and manipulator would be remote. The man can give commands to the machine much as he would to a human slave, i.e., "put nut A on bolt B", and the computer which accompanies the manipulator translates this into detailed movements of motors. The man learns about the results of his commands through necessarily limited capacity displays and possibly with an appreciable time delay of up to several seconds. This type of manipulator would be useful for assembling space stations or life support equipment in space before humans were sent aloft.

Several pieces or peripheral equipment have been built and are now operative. These include a real time clock, a 6-bit digital to analog converter, and logic to run two seven degree-of-freedom manipulators. The manipulator described above uses standard servo-motors and feedback control is accomplished by reading potentiometers. A second manipulator is currently being fitted with stepping motors. These motors move a fixed increment whenever they are pulsed, and supply a holding torque when receiving no input signal. They operate on computer pulses, and no external feedback loop is required if input pulses are counted by the computer.

Work has begun on programming the computer. The initial phase consisted of developing a system of eleven basic subroutines to make the computer-hand hardware a controllable and flexible system. The reason that such a sizeable system of routines is necessary is the drift in position encountered in all 7 degrees of freedom on the manipulator if all 7 motors are not constantly checked and serviced. The system developed in the initial phase is capable of moving several degrees of freedom at a time upon command from the computer's teletype keyboard. At the same time the computer constantly updates a section of memory containing a present as well as several past values of the 7 analog positional sense inputs and 18 binary sense inputs. It will also display on the scope the current condition of the binary sense inputs.

The initial programming phase gives only speed control over the motors. Current work is going forward to enable the operator to issue commands from the keyboard in terms of end goals rather than motor speeds. For instance "move until you hit something with right outside sensor", or "move until sensor changes state".

The final phase will consist of the development of several general subroutines causing the hand to execute a series of movements in several directions to try to fulfill goal specifications. Proposed routines are Level Hand, Scan the Environment, Here is a_i, Grab at a_i, Put at a_i, Go to a_i.

In terms of such a system of routines, it should be possible to begin to define on a quantitative basis the nature of the interaction between a human supervisory operator and a semi-intelligent control system. More practical questions to be answered concern the way in which a man controlled manipulator system for space applications should be built: what degree of touch and vision feedback is necessary, how best should the human operator issue commands - through a symbolic keyboard or through an articulated local model of the remote manipulator, what kinds of instability or other difficulty will be encountered, and etc. A realistic performance criterion for remote manipulation is being sought.

5. Dynamic Programming model of preview control - P. A. Hardin (Certain of the experimental aspects of this work are being coordinated with a U. S. Public Health Service study on simulation of automobile driving behavior in potential collision situations).

A forthcoming paper in the IEEE Transactions on Human Factors[2] summarizes the present point of view in modelling the human operator in tasks where he can preview an input of nonuniform importance. Three models are described, the first an extended impulse response or convolution weighting function, the second a two-time scale analog computing paradigm, with fast-time experiments performed over the extent of the previewed space, the third an optimal control policy based on an implicit penalty function and carried out over the previewed space. The second model is utilized in an S. M. thesis submitted by W. M. Johnson[3] and supported by this grant. The third is described as it applies to the specific context of automobile driving in a paper[4] recently presented to the Highway Research Board.

Work has continued primarily on the third approach, involving optimal control of a dynamic process over a previewed span of input. Several programs are being developed for the 7094 computer which simulate preview control systems and specifically is implemented by means of the dynamic programming algorithm of Bellman.

It is known that animals and man-controlled vehicles typically are self paced, i.e., they speed up on the "straightaways" and slow down on the curves, and implications of such control are being studied on the computer using a second-order dynamical system as controlled vehicle. A second problem of interest is the manner in which an optimal solution on a coarse grid differs from an optimal solution on a fine grid, and whether a grid can be made successively finer and the "tube" of sampled points narrowed on successive iterations of the algorithm. Finally we are interested in other optimal or quasi-optimal techniques such as the gradient method of Bryson.[5]

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